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Abstract

The strength of pairing correlations in the second minimum of superdeformed (SD) or highly deformed (HD) nuclei can be derived from the identification of the discrete linking γ transitions between the SD or HD bands and the ND states. The knowledge of the excitation energy between the two wells allows the evaluation of the mass of the nucleus in its SD or HD shape and the extraction of the gap parameters. In the A=130 mass region such linking transitions have been observed for a series of Nd isotopes with only the exception of the ^{136}Nd nucleus. For this purpose, we have investigated the decay out of the yrast HD band in ^{136}Nd via the reaction ^{110}Pd(^{30}Si,4n)^{136}Nd with a gold backed target. The 130 MeV Si beam has been delivered by the Legnaro Tandem and the EUROBALL multidetector has been used to measure γ^n coincidences. The decay pattern of the yrast HD band to ND states in ^{136}Nd has been analysed and possible discrete linking γ transitions are proposed.

Thanks to these preliminary results neutron gaps for HD shapes in ^{134}Nd and ^{135}Nd have been extracted from odd-even mass difference formulae using different-order Taylor series expansions. The values of the neutron gaps in HD matter are compared to that of the ND matter. Furthermore the influence of increasing rotational frequency on the pairing gaps is considered.

1 Introduction

The study of nuclei in the A=130 mass region at large deformation has been a fertile source of information for various high-spin phenomena, like the coexistence of normal-deformed (ND) and highly-deformed (HD) configurations, the role of shell gaps versus the occupation of the intruder orbitals stabilizing the large deformation, the identical bands. The knowledge of the single-particle excitations in the second well has improved dramatically, but the lack of experimentally-determined excitation energies, spins and parities for the HD states prohibited to infer definitive conclusions. These quantities can be reached through the observation of discrete γ transitions between the lowest levels of the HD band and the ND ones. The first experimental breakthrough in the study of the decay-out process has been achieved in the odd ^{133,135,137}Nd nuclei of the A=130 mass region [1, 2, 3, 4]. In these nuclei the observation of the discrete linking transitions has been favoured by the relatively higher intensity of the HD bands ($\simeq$10% of the reaction channel) as well as by the small excitation energies with respect to the yrast line in the decay-out region ($\simeq$1 MeV). The HD bands in even-even Nd nuclei, based on two quasi-particles (qp) excitations, are much weaker than in the odd ones. The HD intensity is about 1% of the total population of the nucleus. The identification of discrete linking transitions becomes as difficult as in the other regions of superdeformation (A=150, A=190). The resolving power achieved by the new generation of γ-ray spectrometers, like EUROBALL III, now allows transitions with intensities around 10^{-3} of the population of the final residual nucleus to be observed, making therefore feasible the study of linking transitions in these nuclei. Such transitions have been recently observed in ^{132,134}Nd[5, 6].

The strength of neutron (resp. proton) pairing correlations in the second minimum of SD nuclei can be estimated from the knowledge of the excitation energies for a given series of isotopes (resp. isotones). The identification of linking transitions in ^{136}Nd will fix the excitation energy of the HD band and offers the unique possibility to estimate the neutron pairing gap in the second minimum by using a Taylor series expansion of the mass in powers of the nucleon number of interest. For this purpose we have undertaken the study of the decay-out of the yrast HD band in ^{136}Nd with EUROBALL III and in this paper we will present and discuss our preliminary results.

2 Experiment

The experiment was performed at the LNL Legnaro Laboratory with the XTU Tandem accelerator. The ^{110}Pd(^{30}Si,4n) reaction at a beam energy of 130 MeV was used to populate high angular momentum states in ^{136}Nd. The target consisted of a foil of 1 mg/cm^2 of ^{110}Pd deposited on a 10 mg/cm^{2}gold backing. The choice of the reaction and the beam energy were determined by a previous experiment performed with the GASP array[7]. The two most intense channels populated in our reaction were ^{136}Nd and ^{137}Nd (with a ratio $\frac{^{137}Nd}{^{136}Nd} \sim 20$ %). A backed target was used to unambiguously identify the transitions which depopulate the HD band. The γ-ray spectroscopy was done using the EUROBALL III array which consisted of 239 germanium crystals. It is composed of i) 30 tapered germanium detectors placed on three rings at forward angles, ii) at medium angles, 26 clover detectors which are each composed of 4 germanium crystals in the same cryostat and iii) at backward angles, 15 cluster detectors formed by 7 germanium capsules. All these detectors are surrounded by BGO scintillators used for Compton suppression. The detector signals are processed through the VXI electronics which send their data to three event collectors. Finally a processor farm builds the EUROBALL event recorded on DLT tapes. During the five days of experiment, a total of 2.8 $\times 10^9$ four and higher fold coincidence events were collected. Calibration and relative efficiencies of the array were obtained using standard sources over the range of 80 - 3548 keV.

3 Data analysis

From the previous experiments with gold backed-target in the neighbouring nuclei, it results that the transitions of the HD band with energies higher than $E_\gamma \simeq$800 keV suffer from Doppler broadening[4]. On the contrary the transitions de-exciting the lowest levels of the HD band appear as sharp lines in the γ-ray spectra. As the transitions which link the HD band to the ND states are expected to be emitted from stopped nuclei and also to be very weak, it is easily realized that one can enhance their detection by taking advantage of the better energy resolution achieved in backed-target experiment. For an experiment with a thick target, the Doppler correction rule is:

$$E_\gamma^{Detected}(\theta) = E_\gamma^0(1 + F(\tau)\beta_0 cos(\theta)) \tag{1}$$

where $E_\gamma^{Detected}(\theta)$ is the energy detected at an angle θ with respect to the beam axis. E_γ^0 is the center of mass energy of the γ-ray emitted by the recoil nucleus. β_0 is the initial velocity of the recoil nucleus (and has been determined to be 2.06% in our experiment) and $F(\tau)$ is the attenuation factor for each HD level. This factor reproduces the velocity decrease during the de-excitation along the HD band. Starting from the $F(\tau)$ of ^{136}Nd and ^{137}Nd obtained from a previous experiment with GASP, with quite similar conditions, we have adjusted these factors for our experiment.

Various kinds of histograms have been used during this analysis :

i) All 1D spectra were sorted according the method of Beausang et al. [8] to avoid unphysical spikes. The HD gating conditions have been applied by using a different Doppler correction for each HD gate. Usually two spectra have been obtained for a given set of gates : one spectrum with variable Doppler correction, to check the HD gates, and another without correction to search and study linking transitions.

ii) Gated matrices have also been built, with and without Doppler correction. The same gating method with a variable Doppler correction was used.

iii) Finally DCO ratios have been extracted. For this purpose, due to the lack of symmetry of EUROBALL III but in order to take advantage of its large detection efficiency, we have separated the detectors in two sets : the clover detectors on one hand, and all tapered and cluster detectors on the other hand.

4 Results

In order to check the analysis, we have studied the previously known decay-out pattern of the HD band in ^{137}Nd, which is a by-product of this experiment. The results (see fig. 1) show the same discrete linking transitions as in [4] with better statistics and peak to background ratio, demonstrating the pertinence of our data treatment and the power of the EUROBALL III array.

We have then studied the ^{136}Nd HD band with the same prescription. The two kinds of spectra described in section 3 are presented in fig. 2a and 2b. In the first one, γ-rays with energies higher than 717 keV are Doppler corrected, so linking transitions are corrected,

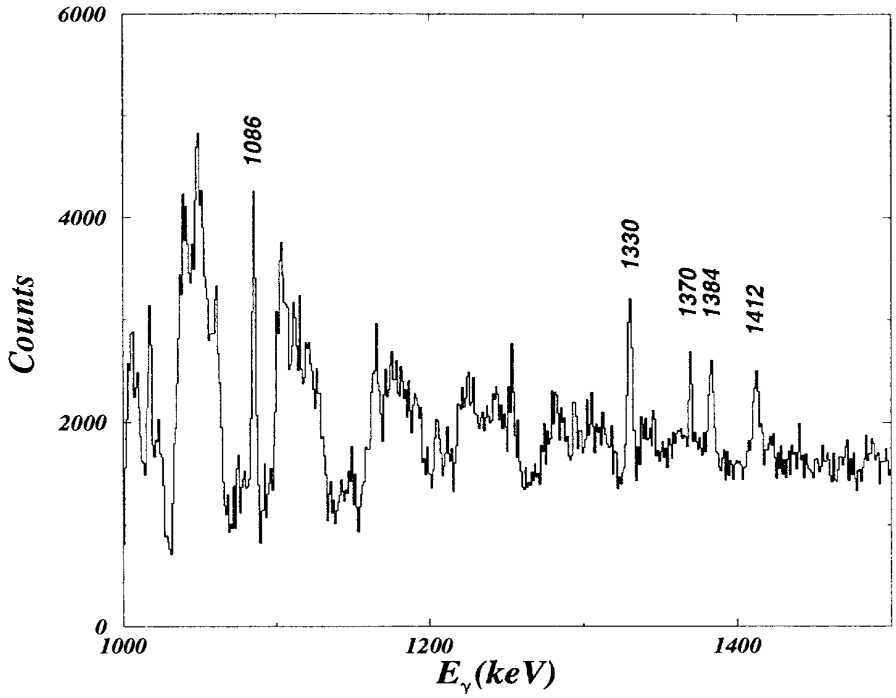

Figure 1: *Double-gated background subtracted spectrum of ^{137}Nd yrast HD band. The energies of the linking transitions between the HD band and the ND states are indicated.*

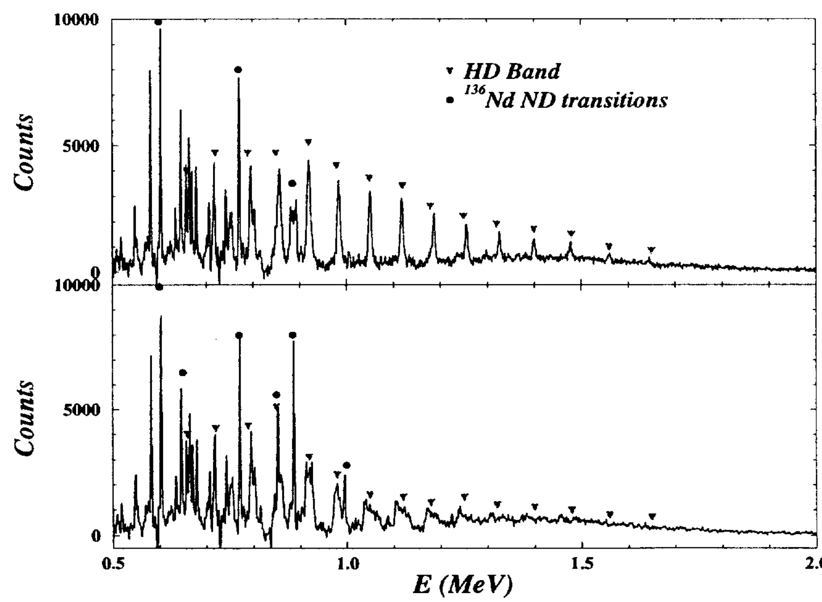

Figure 2: *Double-gated background subtracted spectra of ^{136}Nd yrast HD band. HD transitions are indicated by down triangles and ND transitions by circles. Upper spectrum (fig. 2a) has been Doppler corrected while the lower one (fig. 2b) has not been.*

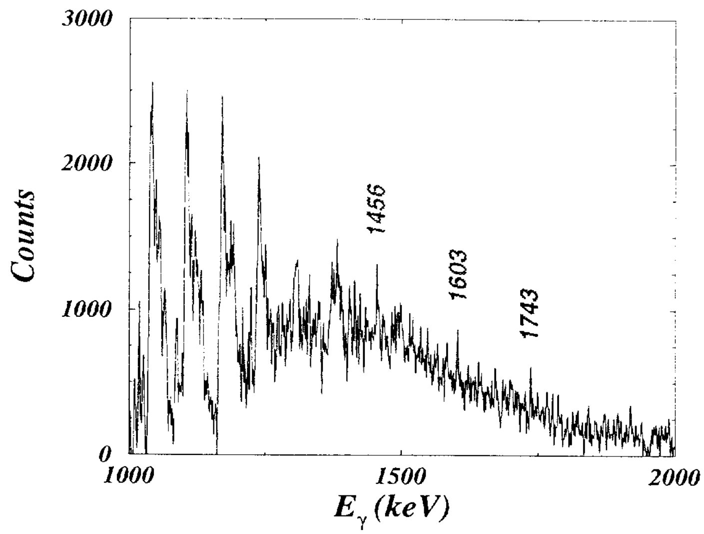

Figure 3: *High energy part of fig. 2b. The energies of the linking transition candidates are marked.*

whereas they have not to be. In the uncorrected spectrum, HD transitions appear as broad bumps while all ND transitions look like sharp lines. This is the clear signature that the HD γ-rays have been emitted during the recoil of the nucleus while ND transitions have been emitted by a stopped nucleus. In this last spectrum, linking transitions, if they exist, should be sharp. A zoom in the high energy part of the spectrum displayed in fig. 2b (see fig. 3), provides 3 candidates which could be implied in the decay-out pattern, namely the 1456, 1602 and 1743 keV lines.

In order to establish the position of these candidates in a decay-out level scheme, we have studied the coincidence relationships between HD and ND transitions. The spectra obtained by double-gating on the 390 keV ND transition and one among two of the lowest transitions of the HD band - either 718-795 keV (fig. 4a), or 795-817 keV (fig. 4b) - show a new sharp line at 1493 keV. It is worth noting that this transition cannot be seen on fig. 4, because it is unresolved in the 1477 keV HD bump. These spectra also indicate the position of the linking transition candidates in a tentative decay-out level scheme. Indeed, the comparison between the spectra 4a and 4b shows that the 1492 keV line is stronger in the first one, the 1456 keV intensity being unchanged. This means that the 1492 keV transition is in coincidence with the 717 keV HD transition whereas the 1456 keV one is not and de-excites the third HD level. A clear coincidence relationship between this 1456 keV line and a new transition (754 keV) has been also observed.

The strongest ND transitions (390, 663, 845 and 1000 keV) fed by the decay out of the HD band belong to the band labelled 3 by Petrache et al [7]. It suggests that the linking transitions reach the ND levels at the 18^+ level de-excited by the 1000 keV line. The sum of (1456 keV+754 keV) and (1493 keV+717 keV) gives 2210 keV, establishing the energy difference between the third low-lying state of the HD band and the 18^+ of band 3. The tentative decay-out scheme is drawn in fig. 6. DCO ratio measurements of the linking transitions show that 1456 keV transition is dipolar ($\Delta I = 1$) while 754 keV transition is quadrupolar($\Delta I = 2$). Assuming the electric character of these transitions, the decay-out proceeds via E1 and E2 transitions. Therefore the lowest state of the HD

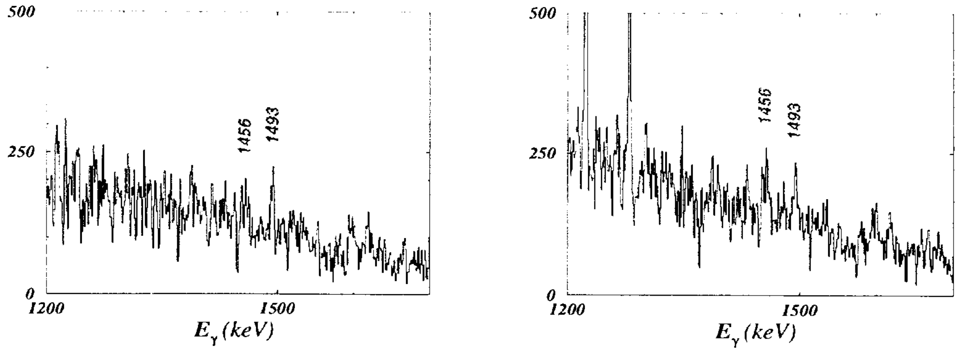

Figure 4: *Spectra gated on the 390 keV ND transition and one among two of the lowest ones of the HD band, namely 717 keV or 795 keV for the left spectrum (fig. 4a) and 795 keV or 857 keV for the right one (fig. 4b).*

band is assumed to have spin and parity 17^- at an excitation energy of 7030 keV.

5 Discussion

The ^{136}Nd HD states excitation energy found in this work is discussed in comparison with those recently determined in the neighbouring Nd isotopes [2, 3, 4, 5, 6]. For the odd Nd isotopes the excitation energy is an increasing function of the neutron number(fig. 7). This is explained by a deformation decrease of the HD bands when increasing neutron number[9]. Indeed all HD bands involve the $i_{13/2}$ intruder orbital, which slopes down with the deformation. Thus the excitation above the Fermi surface of this orbital increases with the neutron number and the excitation energy of the HD bands is higher in the heavier Nd isotopes. The same behaviour occurs in the even-even Nd isotopes : ^{136}Nd HD states excitation energy is higher than the ones of the lighter even-even isotopes (^{134}Nd and ^{132}Nd). Moreover the energy of the bands in even-even nuclei is systematically higher than in the odd ones, confirming that they involve 2-qp configurations.

The knowledge of the HD absolute excitation energy for an extended series of Nd isotopes, allows the pairing strength to be estimated in the second minimum. Indeed, it is well known, for ND matter, that the neutron pairing gap Δ_n (or proton pairing gap Δ_p) can be estimated from the odd-even mass differences. Using a first-order Taylor expansion, the experimental neutron pairing gap in an even-even nucleus takes the following expression [10]:

$$\Delta_n^{even-even} = \frac{1}{2}[M(Z,N+1) - 2M(Z,N) + M(Z,N-1)] \qquad (2)$$

In order to smooth possible local discontinuities a third-order Taylor expansion can be used and leads to :

$$\begin{aligned}\Delta_n^{even-even} = -\tfrac{1}{8}[&M(Z,N+2) - 4M(Z,N+1) + 6M(Z,N)\\ &-4M(Z,N-1) + M(Z,N-2)]\end{aligned} \qquad (3)$$

The same expansion can be done for odd-even nuclei.

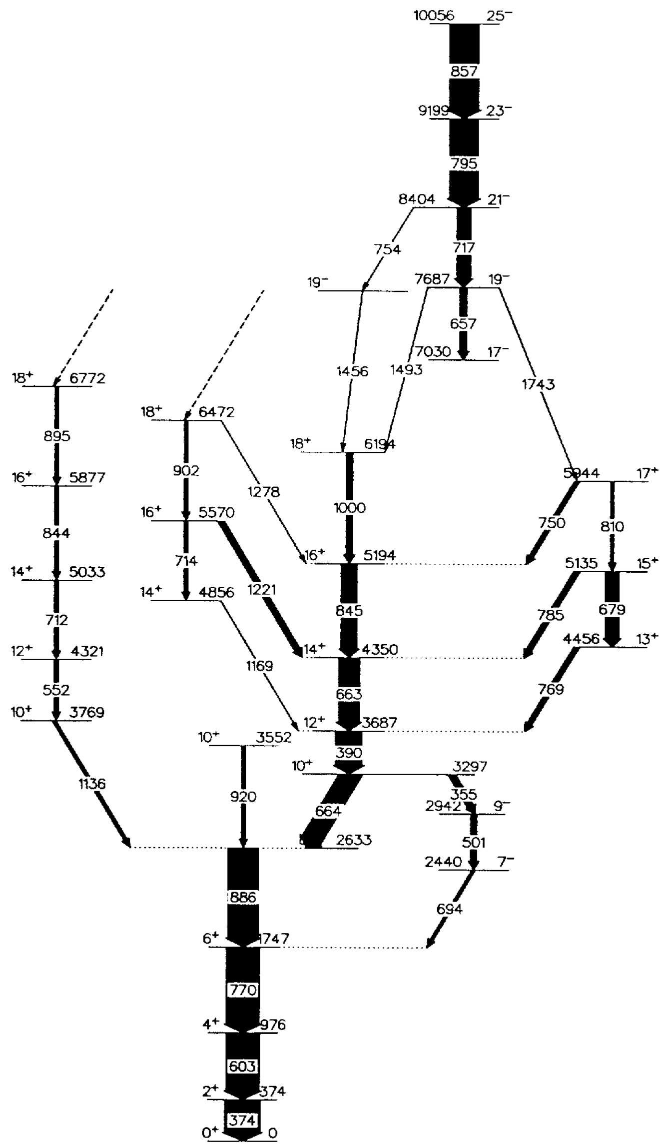

Figure 5: *Tentative decay-out scheme of* ^{136}*Nd yrast HD band.*

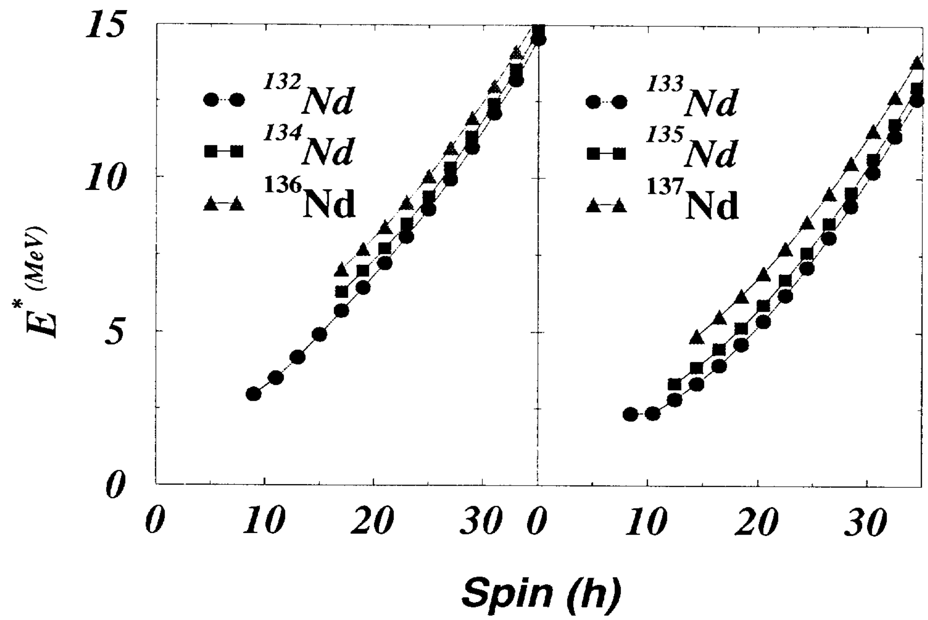

Figure 6: *Comparison of the HD states excitation energies in MeV versus the spin, for the even-even isotopes on the left (fig. 6a) and the odd ones on the right (fig. 6b).*

We attempt to apply the same formulae to the HD nuclei. By replacing the ND masses in eqs. (2) and (3) by the HD ones, it is possible to estimate the neutron pairing strenght in the second well. However in the A=130 mass region, even-even nuclei in their HD shape are stabilized by two qp states. This leads to an opposite sign for eqs (2) and (3). In the HD matter the relevant set of equations for the extraction of the experimental neutron pairing gap is:

$$\Delta_n^{even-even} = -\frac{1}{2}[M^{HD}(Z,N+1) - 2M^{HD}(Z,N) + M^{HD}(Z,N-1)] \tag{4}$$

$$\begin{aligned}\Delta_n^{even-even} = \tfrac{1}{8}[&M^{HD}(Z,N+2) - 4M^{HD}(Z,N+1) + 6M^{HD}(Z,N) \\ &-4M^{HD}(Z,N-1) + M^{HD}(Z,N-2)]\end{aligned} \tag{5}$$

As it is quite impossible to obtain the HD masses at zero frequency, we will suppose that the same formulae remain valid at a given rotational frequency with the following expression :

$$M^{HD}(\omega) = M^{ND}(\omega = 0) + E_{exc}(\omega) \tag{6}$$

where the experimental $E_{exc}(\omega)$ can be understood as the sum of the energy difference between the ND and HD wells at zero frequency and the rotational energy in the second well. So we choose for each nucleus HD states at the same rotational frequency (giving $E_{exc}(\omega)$) and in this way the HD neutron pairing gap can be estimated using eqs. (5) and (6). The results for ^{134}Nd and ^{135}Nd are shown in fig. 7. The main result is that the pairing gap value is reduced approximately by a factor 2 at high rotational frequencies, but pairing correlations still exist. For 2-qp states as discussed by Jain et al. [11] a reducing factor of about 0.8 is expected, but here the quenching is stronger. Nevertheless

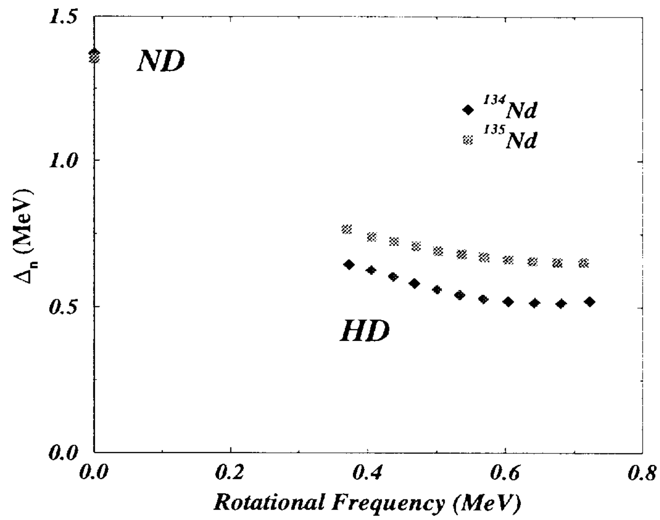

Figure 7: *Experimental neutron pairing gaps in HD bands of ^{134}Nd and ^{135}Nd extracted with eq. (5) as a function of the rotational frequency. For comparison the corresponding ND gaps are also reported at zero frequency.*

our extraction is very rough because we have made crude assumptions : same deformation and same behaviour of the dynamical moment of inertia for the different HD isotopes. However our results are in agreement with the theoretical prescription of Wyss et al.[12] where the pairing decreases gradually with the rotation and is reduced by a factor 2 at a frequency of 0.7 MeV.

To summarize we have observed for the first time discrete γ-ray linking transitions de-exciting the HD band in ^{136}Nd and proposed a decay-out scheme. We have then extracted the first experimental estimation of the neutron pairing gap in the HD matter at high spins. The major conclusion is that the pairing correlations still exist in the highly-deformed bands of the A=130 mass region. But microscopic self-consistent Cranked Hartree-Fock-Bogoliubov calculations are highly desirable in order to quantify the quenching of the neutron pairing gap.

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References

[1] D. Bazzacco et al. *Phys. Lett. B* 309, p.235, 1993.

[2] D. Bazzacco et al. *Phys. Rev. C* 49, R2281, 1994.

[3] M. Deleplanque et al. *Phys. Rev. C* 52, R2302, 1995.

[4] S. Lunardi et al. *Phys. Rev. C* 52, p.R6, 1995.

[5] C. Petrache et al. *Phys. Lett.* 451, p.223, 1997.

[6] C. Petrache et al. *Phys. Rev. Lett.* 771, p.956, 1996.

[7] C. Petrache et al. *Phys. Lett. B* 219, p.275, 1996.

[8] C. Beausang et al. *Nucl. Instrum. Methods Phys. Res. A* 364, p.560, 1996.

[9] S. Mullins et al. *Phys. Rev. C* 45, p.2683, 1992.

[10] D. Madland and J. Nix. *Nucl. Phys. A* 476, p.1., 1988.

[11] K. Jain et al. *Phys Lett. B* 322, p.27, 1994.

[12] R. Wyss et al. *Phys. Lett. B* 215, p.211, 1988.